Nuclear Explosion Near Surface of Asteroids and Comets: Common Description of the Phenomenon

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Abstract

Nuclear explosion at the NEO, such as asteroid or comet, may have consequences of two main types:

- *disintegrate the NEO into the fragments of such size and impart such velocities on the fragments, that near the Earth the NEO fragments will appear to be at large distances from one another, and will partially pass by the Earth, partially burn in the upper atmosphere without affecting its surface;*
- *without damaging the NEO impart such a momentum, which will change the NEO trajectory and provide its safe passing by the Earth.*

Respectively, two main problems arise, which need to be solved for assessing feasibility of creating the system of the Earth protection on the basis of nuclear weapons and for determination of such system parameters:

- *predict state of the NEO after the nuclear explosion near its surface;*
- *assess the momentum transferred to the NEO as the result of the nuclear explosion near its surface.*

It is possible to influence the NEO by nuclear explosions of different types: buried explosion, surface explosion, and stand-off explosion. Each type has its own peculiarities.

This report considers peculiarities of the three types of nuclear explosions in association with the above formulated problems. A short description of the processes and characteristic parameter values are given. A feasibility of schematizing the phenomena of the surface and buried explosions within the concept of explosion "equivalence" is discussed. Peculiarities of numerical description of the explosions and possibilities to calibrate the numerical methods using the experimental data on underground nuclear explosions and cratering experiments are discussed. The issues of the numerical assessment accuracy are considered and the strategy of the nuclear explosion calculations within the framework of the asteroid problem is proposed.

Introduction

Nuclear explosion at the near-Earth-object (NEO), such as asteroid or comet, may have consequences of two main types:

— disintegrate the NEO into the fragments of such size (<10...30 m) and impart such velocities (>0.1...1 m/s) on the fragments, that near the Earth the NEO fragments will be at large distances from one another and burn in the upper atmosphere without affecting the surface of the Earth;

— without damaging the NEO impart such a momentum, which will change the NEO trajectory and provide its safe passing by the Earth.

Respectively, two main problems arise which need to be solved for assessing feasibility of creating the system of the Earth protection on the basis of nuclear weapons and for determination of such system parameters:

- predict state of the NEO after the nuclear explosion near its surface;
- assess the momentum transferred to the NEO as the result of the nuclear explosion near its surface, i.e. assess velocities at which the NEO fragments will be ejected from its surface.

The NEO can be affected by nuclear explosions of different types: buried explosion, surface explosion, and stand-off explosion. Each type has its own peculiarities both in physical pattern of the phenomenon, and in technical design of respective nuclear module. Without considering the subject of affecting asteroids of complex shape or very large dimensions that may require several consecutive or simultaneous explosions, we would like to discuss the general pattern of single explosion near the asteroid surface, and to discuss experimental and theoretical basis which will enable to find certain engineered solutions.

Below we consider the different types of the nuclear explosions, the determining processes and characteristic parameters.

Underground Contained Explosions

Release of main fraction of energy during the nuclear explosion takes place within approximately one hundredth of a microsecond, and as result of this pressure in nuclear explosive device reaches value of hundreds of megabars (1 bar = 10^5 N/m^2 = 1.02 atm) under temperature of several kev (1 kev = 1.16• 10^7 °K).

Density of initially released energy is so high that its transfer occurs mainly by radiant heat conductivity. It results in propagation of thermal wave in the ground [1]. While the dimensions of the region involved in the movement increase, the temperatures decrease, and the flow becomes of purely gasdynamic character. This leads to formation of gasdynamic source determining the subsequent evolution of the explosion. Characteristic energy density in such gasdynamic source is ~10 kJ/g. It can be shown [2] that the processes of the energy transfer by radiation become minor when the ground layers with radius more than 0.2 m/kt$^{1/3}$ are involved into the movement. Beginning from approximately this moment a strong shock is released. While the shock is propagating its intensity is decreasing, and as the result, at different distances from the explosion center zones of evaporation, melting, fragmentation, and fracturing are consecutively formed, and elastic wave (seismic wave) is released.

As it is known [3], development of processes under powerful explosions in infinite uniform medium has similarity. This means that all spatial (cavity radius, radii of the fragmentation and fracturing zones, etc.) and time (time of the cavity formation, etc.) characteristics of the explosion alter with the explosion yield E change proportionally to $E^{1/3}$.

The explosion at sufficient depth doesn't destroy the earth surface. Such explosion is called contained. Without considering some details, such as formation of spall lens on the ground surface, the contained explosions can be regarded as explosions in infinite medium.

Data obtained from underground nuclear explosions comprise and will comprise the basis for calibration of calculation methods for determining effect of nuclear explosion on asteroids due to:

- large number of conducted tests;
- variety of media in which the tests were performed (coral reef, alluvium, rock-salt, limestone, granite, basalt);
- detailed experimentation accompanying the tests.

To such data we refer the following:

- motion laws and parameters of the shock wave (in the region r<5...10 m/kt $^{1/3}$ where the strength effects play minor role);
- parameters of seismic explosion waves in the zone of elastic-plastic flows;
- parameters of irradiated seismic (elastic) wave;
- amount of rock irreversible evaporated in the shock wave (≈70 t/kt);
- amount of rock melted in the shock wave (~500...900 t/kt);
- dimensions of intensive fragmentation zones (~25 m/kt$^{1/3}$);
- dimensions of fracturing zones (~100 m/kt$^{1/3}$);
- distribution of fragments of rock disintegrated in the shock by dimensions;
- dimensions of the formed cavity (from 9..11 m/kt$^{1/3}$ in rock-salt, granite, and dolomite up to 14...17 m/kt$^{1/3}$ in alluvium and tuff).

Experience of the underground nuclear explosions, numerous published and not published calculation results identify that without speaking about physics of nuclear device operation, by now scientists have studied well and with high accuracy described in calculations the equations of state for terrestrial rocks, their elastic-plastic properties, and (by one-dimensional methods) the main parameters of flows appearing during the underground explosions.

It should be pointed out that during the underground nuclear explosions a very intensive fragmentation of rocks takes place [4], and maximum dimensions of the formed rock fragments are ~5 m. This makes us hope that affecting the steroid we'll be able to achieve not only considerable change in its momentum, but also to provide its necessary fragmentation.

Nuclear Surface Explosions

To change the trajectory or to disintegrate the asteroids with diameter exceeding 50...100 m we'll need nuclear device having yield of 1 Mt and more. This proceeds from values of the above given characteristic dimensions of the destruction zones during the underground nuclear explosions. Therefore, we consider the surface explosion of rather powerful nuclear device (thermonuclear) at the height on the order of 1 m.

The ground motion during the explosion near its free surface is determined primarily by the fraction of the explosion energy transferred directly to the ground. In the modern thermonuclear charges the duration of the energy release is on the order of one hundredth of a microsecond [2]. If the device is exploded above the asteroid surface the main part of released energy will be radiated out of the nuclear device in the form of x-rays during a time period of several hundredths of a microsecond. The part of the x-radiation directed downwards illuminates the asteroid surface in the form of short pulse of quanta. This will cause its radiation heating which will be completed within tenths of a microsecond, and this leads to formation of high temperature region of ground having the lens shape.

Temperature in the ground is so high during that (~1 kev) that on one side a thermal wave propagates in the ground, and on the other side, intensive reradiation from the surface into air proceeds. This results in absorption of small fraction of the radiation energy (less than 10%) by the ground. Even less fraction of the energy is transferred to the ground due to impact of the nuclear device vapors. After the thermal wave stops in the ground the shock is released. When the shock propagates through the ground its intensive destruction takes place. Due to rarefaction from the surface the ground moves back, upwards. As the result, the ground mass is thrown upwards at high velocities, and a crater is formed.

Quantitative characteristics and some qualitative peculiarities of the surface explosion phenomenon have been considered in details , e.g. [2, 5]. In particular, it appears to be that:

- fraction of the full explosion energy transferred to the ground depends little on the explosion yield over the range 0.1...10 Mt (at least this value is more sensitive to details of the nuclear device design which, in their turn, determine share of the explosion energy irradiated in the form of x-ray rays, the radiation time and spectrum);
- the fragmentation region has approximate shape of hemisphere with radius ~100 m/Mt$^{1/3}$;
- momentum transferred to the asteroid makes up ~10^8 (t·m/s)•Mt.

Calculations of the surface explosions are most complicated compared to other types of the explosions. This is associated with the necessity to describe large strains during the impact of the nuclear module vapors into the ground and during the ground scattering with simultaneous account for energy transfer by radiation. Besides that, for the surface explosion the approximation of radiant heat conductivity is not always applicable, we need to take into account the spectral effects. For example, temperature of radiation leaving the surface of the nuclear module, and temperature in the heating lens can differ significantly.

A special problem in calculational description of the surface explosions is caused by almost absolute absence of the experimental data. To avoid strong radioactive contamination of the test sites the surface explosions were not conducted during nuclear weapons testing.

Nuclear Shallow Bursts

Effect of the nuclear explosion on asteroid will be the strongest if the nuclear device is buried into the ground before the explosion. This is associated with the fact that during such type of the explosion, unlike the surface and stand-off explosions, the explosion energy at initial (thermal) phase of the phenomenon evolution is transferred to the asteroid ground practically completely. So, at depth-of-burst (DOB) exceeding 2 m/Mt$^{1/3}$ the thermal wave doesn't reach the ground surface, the full energy at the initial stage remains in the ground. At subsequent increase of the explosion depth the depth at which the rarefaction wave from the free surface overtakes the shock propagating downwards also increases. The explosion effect increases respectively. As the result of this process the effect of the buried explosion on the asteroid turns to be equivalent to effect of the surface explosion with yield tens of times higher [2. 5, 6]. Therefore, consideration of affecting the asteroid by the buried explosion is of especial interest.

Apparently, really achievable values of the DOB are within the limits of the first tens of meters. Therefore, using the nuclear modules having yield of ~1 Mt and more the values of the scaled DOB of practical interest for us are 0.2 up to 3...5 m/kt$^{1/3}$. For such depths the characteristic value of momentum transferred to the asteroid will be ~10^9.10^{10} (t·m/s)·Mt. Dimensions of the fragmentation zone will be at least two times larger than the dimensions of the fragmentation zone of the surface explosion of the same yield. For DOBs of 6...8 m/kt$^{1/3}$ radius of the fragmentation zone will exceed the fragmentation radius of the contained explosion, since the rarefaction wave from the free boundary will overtake the shock propagating downward at the distance ~25 m/kt$^{1/3}$, and additional fragmentation will be provided by the spall phenomena in the zone of intensive development of radial fractures.

Unlike the surface explosion the calculational description of the buried explosion initial phase currently is not difficult. At the same time at the phase of the explosion crater development we have to face the problem of adequate description of elastic-plastic flow with large strains.

Experimental data on the nuclear explosions which can be referred to the shallow bursts are rather poor. Table 1 shows the list of all nuclear cratering explosions conducted in the USA and the USSR [7]. From among 16 specified explosions most of them were carried out at depth close to optimum for obtaining maximum dimensions of the crater, but which are of less interest for the asteroid problem. It should be also pointed out that effect of the buried explosions on the Earth is to large extent determined by the gravity influence. This also hampers use of the experimental data for the calibration.

Table 1. Summary of Nuclear Cratering Explosions [8,9]

Name	Yield kt	Depth-of-burst, m	Crater radius, m	Crater depth, m	Medium
Jangle S	1.2	1.1	14	6.4	Alluvium
Jangle U	1.2	5.2	40	16	Alluvium
Teapot ESS	1.2	20	45	27	Alluvium
Neptune	0.115	31	31	11	Tuff
Danny Boy	0.42	34	33	19	Basalt
Johnnie Boy	0.5	0.53	18	9.1	Alluvium
Sedan	100	194	184	98	Alluvium
Palanquin	4.3	85	36	24	Rhyolite
Cabriolet	2.6	52	54	37	Rhyolite
Buggy	1.1	41	76	21	Basalt
Row of 5		spacing 46			
Schooner	35	108	130	63	Tuff
1003	1.1	48	53.5	31	Siltstone
1004	~125	~178	204	100	Sandstone/shale
T-1	0.2	31.4	40	21	Sandstone
T-2	0.2	31.4	32.5	16	Sandstone
Row of 3		spacing 40			
Pechora-Kama	15	~127	150 .. 170	10 .. 15	Alluvium
Row of 3					

On the other hand, we have rich experimental data on the buried explosions of chemical HE. To use these data we need additional calculation efforts. Some of the experimental data on the chemical HE explosions directly identify that hopes for sufficiently accurate calculation description of the buried explosion effect on the asteroid may not come true, especially taking into account our limited knowledge on properties of a specific NEO we'll need to affect. So, in the classical review [6] it is pointed out that the most numerous data on explosions of a given yield and in a given ground were obtained in the experiments with 256-pound spherical charges of TNT in alluviums of Nevada Test Site and Albuquerque Test Site. It turned out that volumes of the craters at a given depth changed from one experiment to another by the factor of 2...3. and systematic deviations associated with the test site difference turned to be less than deviations within each test site. This may mean that the experimental data on the craters under conditions of limited knowledge of the ground properties can't be the serious basis for the numerical method calibration, at least, while computing such characteristic as the momentum transferred to the asteroid. This conclusion is also confirmed by characteristics of the craters of the nuclear explosions Jangle S and Johnnie Boy.

During the buried nuclear explosion, as during the contained explosion, a very intensive fragmentation is provided. Table 2 gives some data on dimensions of rock fragments formed during explosions [8,9]. These data show that by nuclear explosions we can provide disintegration of asteroids into fragments with dimensions sufficient for their burning in the Earth's atmosphere.

Table 2. Dimensions of Rock Fragments Formed During Nuclear Cratering Explosions [8,9]

Name	Medium	Yield, kt	Minimum size, m	Medium size, m	Maximum size, m
Sulky	Basalt	0.085	0.03	0.55	4.0
Danny Boy	Basalt	0.42	0.006	0.36	1.8
Palanquin	Rhyolite	4.0	—	0.1	—
Cabriolet	Rhyolite	2.6	0.015	0.061	1.2
Schoolner	Tuff	35	—	0.6	6.0

Stand-off Nuclear Explosions

The nuclear explosion at rather large altitude over the asteroid surface turns to be also effective. This is associated with absence of air which under terrestrial conditions causes transformation of high temperature radiation from the nuclear device into relatively low temperature radiation in air thermal wave.

As the stand-off explosion we call the explosion during which the thermal wave propagation in the asteroid matter is weak or absent, and the reradiation is minor. Such explosion mode is realized when the explosion height exceeds approximately 10 $m/Mt^{1/3}$.

During the stand-off explosion the x-ray radiation from the nuclear module surface falls onto the asteroid and heats up the surface layer. This causes corresponding gasdynamic phenomena: scattering of evaporated surface layer accompanied by the shock propagation and scattering of partially evaporated and disintegrated matter. It is evident that selecting the explosion height at a given yield of the nuclear device we can achieve the situation when initial temperatures of the surface layer are sufficiently small to exclude the reradiation from the free surface. Respectively, we can achieve higher explosion energy withdrawal by the asteroid ground than in the case of the surface explosion.

The processes during the stand-off explosion can be illustrated by simple estimates. If the ground heat conductivity and the reradiation are not significant, then in the problem of dissipation of gas having density at instantaneous energy release in a layer with characteristic thickness z there are two dimensional parameters:

$[\varepsilon]=kJ/cm^2$, $[\rho]=g/cm^2$, $[z]=cm$,

out of which we can compose the only combination with the momentum dimension:

$$I = \xi\sqrt{2\varepsilon\rho z}$$

Accounting for the evaporation energy q which is near 4 kJ/g for silicate rocks, this expression will become the following:

$$I = \xi\sqrt{2(\varepsilon - q)\rho z}.$$

From this simple expression we can make several important conclusions on the character of the momentum change with increase of the incident radiation intensity and the thickness of the heated layer. In particular, it is easy to show, the momentum depends upon the angle of the incident radiation as $I(\beta) = I(\beta = 0)\bullet\cos\beta$. The latter expression is confirmed with high accuracy (~1%) by numerical calculations [11].

In the case of small energy release when the momentum withdrawn by initially evaporated matter significantly exceeds the spall momentum the problem under consideration can with some approximation be reduced to the problem of the gas layer dissipation near a rigid wall at instantaneous uniform energy release. This problem has an analytical solution according to which ξ depends little on the gas adiabat index γ and makes up $\xi \approx 0.8$ [10].

In the case of higher energy release we need to take into account additional evaporation of matter in the shock and the spall momentum, and it is possible to obtain appropriate estimates only within the framework of numerical calculations, though the similarity ideas mentioned above remain in force.

Thus, increase of momentum transferred to the asteroid during the stand-off explosion can be achieved by increasing the energy release in the surface layer (owing to increase of the radiation flow intensity), increasing thickness of this layer (e.g. by changing spectrum of the incident radiation), and increasing area of the asteroid irradiated surface (increasing the explosion height). It is evident, that for each specific asteroid and the specific nuclear module we'll have a certain optimal (in terms of maximum effect) explosion height.

Thus, the problem of computing the x-ray radiation effect of the stand-off explosion on the asteroid involves determination of density of energy released in the surface layer and determination of formed gasdynamic flows at different levels of the radiation. For the stand-off explosion above the asteroid due to relatively small (compared to the asteroid dimensions) thickness of the layer in which the gasdynamic processes develop, the calculations can be done in one-dimensional approximation (with account for the radiation incidence angle). Currently it is not difficult to carry out such calculations.

While considering effects of the stand-off explosion on an arbitrary asteroid, unlike the surface explosion and shallow burst, we are faced with a purely engineered problem of results representation associated with the multi-parameter character of the problem. The effect on the asteroid, besides the explosion yield, height, the asteroid dimensions, will significantly depend upon its shape, chemical composition, density, strength, spectrum of radiation released from the nuclear module. And what's more, even such details as presence of a thin layer of dust on the asteroid surface will significantly influence the value of the momentum transferred to the asteroid. For example, the numerical calculations showed [11] that at values of full flow of the incident radiation of 10^4 kJ/m^2 up to 10^6 kJ/m^2:

- the spall strength change by an order causes change in the momentum by several times;
- at porosity of 30% the momentum decreases several times compared to the rock with zero porosity.

Therefore, to take effective engineered decisions while considering the issues of the Earth protection against asteroids we need to develop a set of typical asteroid models, and compute effects of the stand-off explosion for them

According to the above, in this report we only consider several parameters. Table 3 shows characteristic values of the momentum during the silicate rock surface irradiation by normally incident flow of x-rays of nuclear explosion of Planckian spectrum with temperature T_{eff} for several values of the full flow [11].

In the case of the stand-off explosion with the yield of 1 Mt above the asteroid having the spherical shape with radius 750 m the momentum transferred to the asteroid will be maximum at the height ~200...250 m and will be equal to $\sim 4 \cdot 10^6$ t·m/s for $T_{eff} = 3$ keV, $\sim 30 \cdot 10^6$ t·m/s for $T_{eff} = 15$ keV and $\sim 60 \cdot 10^6$ t·m/s for $T_{eff} = 30$ keV. The latter value is close to the value of momentum transferred to the asteroid during the surface nuclear explosion of the same yield.

Table 3. Momentum (t/m·s) transferred to the silicate rock surface during its irradiation by normally incident x-rays of planckian spectrum with temperature T_{eff}

Full flow kJ/m^2	T_{eff} = 3 keV	T_{eff} = 15 keV	T_{eff} = 30 keV
10^4	~0.5	~0.9	~0.6
10^5	~2	~9	~10
10^6	~8	~60	~100

Conclusions and Discussion

The nuclear explosion phenomenon has been studied pretty well both from the theoretical and experimental points of view. A great progress has been achieved in the sphere of mathematical simulation of the processes taking place during the nuclear explosion. However, this doesn't mean that we can predict result of the explosion near the asteroid surface with high accuracy. This is associated with two circumstances:

- the process of nuclear explosion near the asteroid surface has a number of specific peculiarities which we practically haven't come across during the underground nuclear testing under terrestrial conditions;
- physical properties of material composing the asteroids are practically unknown for us, or known with very high error (for brevity we'll subsequently call the matter of the asteroid or comet, the asteroid ground, or just the ground).

However, the situation is not so bad as it may seem at first sight. The accumulated experience of the underground nuclear testing allows us to state that we know rather well and describe with calculations the properties of terrestrial grounds and propagation of the shock under sufficiently high pressures — up to amplitudes corresponding to the ground destruction.

Using the nuclear explosions we can provide very intensive effect on the asteroids. In this case the most intensive will be the buried explosion effect. The surface and stand-off explosions provide approximately the same effect from the standpoint of momentum transferred to the asteroid. The surface explosion provides more intensive fragmentation of the asteroid than the stand-off explosion.

From the standpoint of numerical simulation it is most easy to describe the stand-off explosion, and the most complicated are the surface explosions. The most valid numerical estimates of affecting the asteroid can be obtained for the buried explosion, the less valid — for the stand-off.

As a whole, under conditions of the limited knowledge of a specific asteroid properties assessment of the necessary yield of the nuclear module may change by several times depending upon the proposed parameters of the asteroid ground. Respectively, from the engineering point of view, to provide the guaranteed achievement of the effect the yield of the nuclear module must be somewhat excessive.

Schematizing Nuclear Explosion Phenomenon (Engineered Approach) and Possible Directions of Future Research

To take engineered decisions it is expedient to have a single approach to at least some part of the above described types of the explosions. Such a single approach as applied to the asteroid problem is possible if we somehow schematize the phenomena of the surface and buried explosions.

Then, within the framework of the asteroid program we'll be interested in processes of the shock propagation in the ground, the crater formation and the ground ejecta. At any type of the nuclear explosion at the asteroid we can separate a main region of effective energy release with energy E_g:

- the region heated through by the thermal wave at the buried explosion;
- the lens of heating and the nuclear charge vapors at the surface explosion;
- thin layer of the ground of a large area in the case of explosion at a considerable height above the asteroid surface.

Therefore we may introduce some coefficient $\eta_t(E_o,H,C)$, such as $E_g = \eta_t E_o$. Subsequently we'll call this coefficient the coefficient of thermal phase equivalence.

We can conveniently schematize the phenomenon at the phase of gasdynamic and elastic-plastic movement using the dimension theory. Select dimensions of mass M, length L, and time T as the basis. Designate the parameter A dimension, as it is commonly used, with the symbol [A]. After completion of the processes of energy transfer by radiation the explosion evolution near the surface of uniform semi-space will be determined by the following system of dimensional and dimensionless parameters:

E_0 - is full energy released during the explosion $[E]=ML^2T^{-2}$;

E_{gi} - full energy of the i-th region of effective energy release in the scheme of the phenomenon development assumed by us, and which corresponds to completion of the thermal phase of the explosion evolution (the full energy of the i-th gasdynamic source) $[E]=ML^2T^{-2}$;

r_{gi} - is characteristic dimension of the i-th region of the effective energy release corresponding to completion of the thermal phase $[r_{gi}]=L$;

H - is depth of the explosion $[H]=L$;

ρ_{oo} - is the ground density $[\rho_{oo}]=ML^{-3}$;

c_o - is characteristic sound velocity, e.g. dimensional parameter in the equation of state $[c_o]=LT^{-1}$;

ρ_o - is characteristic density, e.g. dimensional parameter in the equation of state having the meaning of the grain density $[\rho_o]=ML^{-3}$;

γ_i - are adiabat indices for the material of the i-th region (dimensionless);

c_p - is velocity of elastic p-waves $[c_p]=LT^{-1}$;

ν - is Poisson's coefficient (dimensionless);

k - is coefficient of internal friction (dimensionless);

Λ - is dilatance rate (dimensionless);

Y_o, σ_o - are strength limits for compression and destruction, and their analogs under conditions of plasticity and destruction $[Y_o]=[\sigma_o]=ML^{-1}T^{-2}$.

For terrestrial conditions we must also include another several parameters, such as acceleration of free fall g, initial air pressure, etc., which play a certain role at various phases of the explosion.

Select as the basis parameters the explosion energy E_0, characteristic sound velocity c_0, and characteristic density ρ_o. It is known [3] that out of the selected parameters we can formulate the only combinations with dimensions of length and time:

$$R_d = \left(\frac{E_0}{\rho_o c_o}\right)^{1/3}, \quad td = \frac{1}{co}\left(\frac{E_0}{\rho_o c_o}\right)^{1/3}$$

Respectively, any characteristic of the explosion evolution A will be the function of the dimensional parameters and dimensionless combinations:

$$A = [A] \cdot f\left(\frac{r}{R_d}\ \frac{t}{t_d}\ \frac{H}{R_d}\ \frac{r_{gi}}{R_d}\ \frac{E_{gi}}{E_0}\ \vartheta\ C\right),$$

where [A] is the combination of the basis parameters with dimension of A; r, ϑ -are spherical coordinates (we assume the flow being axisymmetric), and the set C includes all the other parameters:

$$\frac{\rho_{00}}{\rho_0},\ \frac{c_p}{c_0},\ \frac{\sigma_0}{\rho_0 c_0^2},\ \nu,\ \frac{Y_0}{\sigma_0},\ \gamma,\ \text{etc.}$$

Now consider some radius R_h corresponding to some characteristic pressure, or the shift value, or the shift rate at the shock front:

$$R_h = \left(\frac{E_g}{\rho_0 c_0^2}\right)^{1/3} \cdot f\left(\frac{H}{R_d}\ \frac{\rho_g}{R_d}\ \vartheta\ C\right),$$

where f has the meaning of the dimensionless radius and , generally speaking, for the characteristics interesting for us, it is much more than one. Consider

$$\ln f = \ln f(0,0,\vartheta,C) + \frac{\partial f}{\partial \overline{H}}\frac{\overline{H}}{f} + \frac{\partial f}{\partial \bar{r}_g}\frac{\bar{r}_g}{f} + 0\left(\frac{\overline{H}}{f}\frac{\bar{r}_g}{f}\right),$$

where $\overline{H} = H/R_d$, $\bar{r}_g = r_g/R_d$.

Ignoring the terms of the second order, we obtain the following:

$$f = \phi(\overline{H}, \bar{r}_g, C) \cdot f_0(\vartheta, C).$$

Introduce the following designations

$$\eta_g = \phi^3,\ E_{eff} = \eta_g E_g = \eta_t(E_0, H, C) \cdot \eta_g(\overline{H}, \bar{r}_g, C) \cdot E_0 = \eta \cdot E_o$$

Then

$$R_h = \left(\frac{E_{eff}}{\rho_0 c_0^2}\right)^{1/3} f_0(\vartheta, C) \quad .$$

Thus, if $H << R_d$, $r_g << Rd$, then beginning from some moment of time details of the gasdynamic source are forgotten, and the flow similarity of a new type is formed, when the solution can be presented in the form:

$$A = [A] \cdot F\left\{\frac{r}{R_{eff}}\ \frac{t}{t_{eff}}\ \vartheta\ C\right\},$$

where

$$R_{eff} = \left(\frac{E_{eff}}{\rho_0 c_0}\right)^{1/3},\ t_{eff} = \frac{1}{c_0}\left(\frac{E_{eff}}{\rho \rho_0 c_0}\right)^{1/3},\ E_{eff} = \eta \cdot E_e,\ \eta = \eta_t(E_0, H, C) \cdot \eta_g(\overline{H}, \bar{r}_g, C).$$

Thus, despite of the significant differences in the initial phase, the gasdynamic flows of the ground during the surface explosion, explosions at small enough depth and height possess the geometrical similarity with some coefficient proportional to $E_{eff}^{1/3}$, where E_{eff}, is the explosion effective energy determined in a special manner. In such form the last expression is the expression of "the principle of equivalency" [5, 12]. This principle states that the explosion having yield E_1 at some scaled depth $\overline{H}_1$ is equivalent to the explosion having yield E_2 at the scaled depth $\overline{H}_2$ by the flow parameters at large distances.

For the explosions at some depth the moment of the beginning of the approximate geometrical similarity realization is determined by time of rarefaction wave arrival from the free surface, and respectively, by the explosion depth. In particular, if , $H \ll R_d$, the similarity establishes at the gasdynamic phase of the explosion evolution when the strength properties of the medium are practically insignificant. If the explosion depth H exceeds R_d by several times the flow similarity won't be observed.

The described similarity of the explosions is really observed in the numerical gasdynamic calculations. This means that detailed calculations of the nuclear explosion with account for elastic-plastic properties of ground can be carried out for several classes of grounds (e.g. strong rock with density , $\rho \sim 2.7$ g/cm^3, soft ground with density $\rho \sim 2$ g/cm^3, ice) at some given yield and rather small depth of the explosion. The explosions at other depths can be described, having determined values of the coefficient η on the basis of gasdynamic calculation of the initial phase only.

To carry out such comparison it is convenient to use calculations of powerful explosions at the depth of ~2 m/Mt$^{1/3}$ taking such an explosion as a bench-mark. In this case the initial phase of the explosion requiring the energy transfer by radiation is of one-dimensional character and is easy for being described. At the same time, the chosen depth is significantly less than the dynamic radius for the grounds R_d~40...50 m/Mt$^{1/3}$, and the flow phase corresponding to the geometrical similarity is established quickly enough.

When the asteroid hits the ground surface at sufficiently high velocity we may also expect the similarity of the formed flow with the flow in the case of the nuclear explosion at small depth. This will enable, after computing the value η for the asteroid impact, to use the earlier obtained results of calculations and experiments for the nuclear explosions.

In our opinion, a possible direction of work in the sphere of physics of nuclear explosion effect on the asteroids and comets can be computation of coefficient η for several typical asteroid models (which must be developed). Such work will enable to coordinate the efforts of physicists and mathematicians from different laboratories and to provide engineers and designers with the tools necessary for developing the basic characteristics of the system of the Earth protection against the near-Earth-objects. RFNC-VNIITF plans to do some part of this work within the framework of the International Science and Technology Center.

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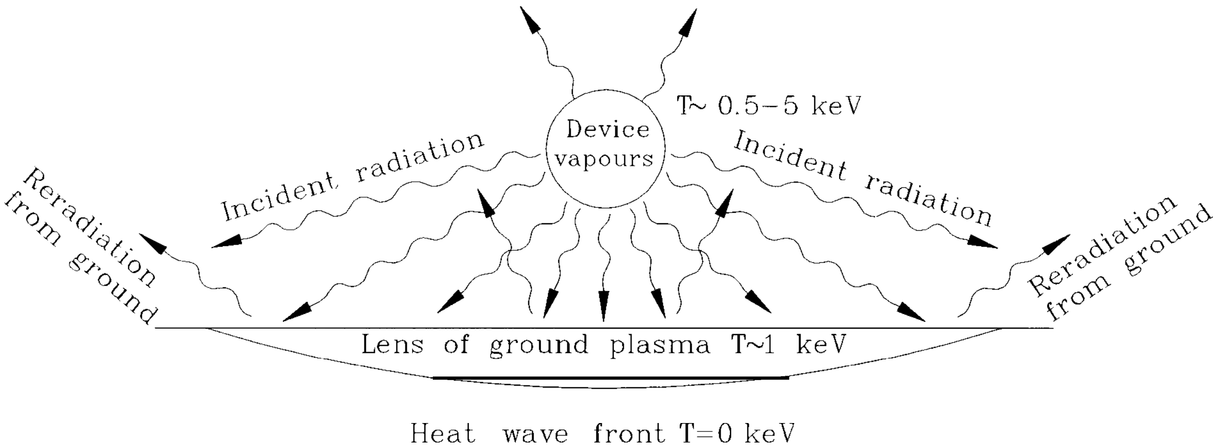
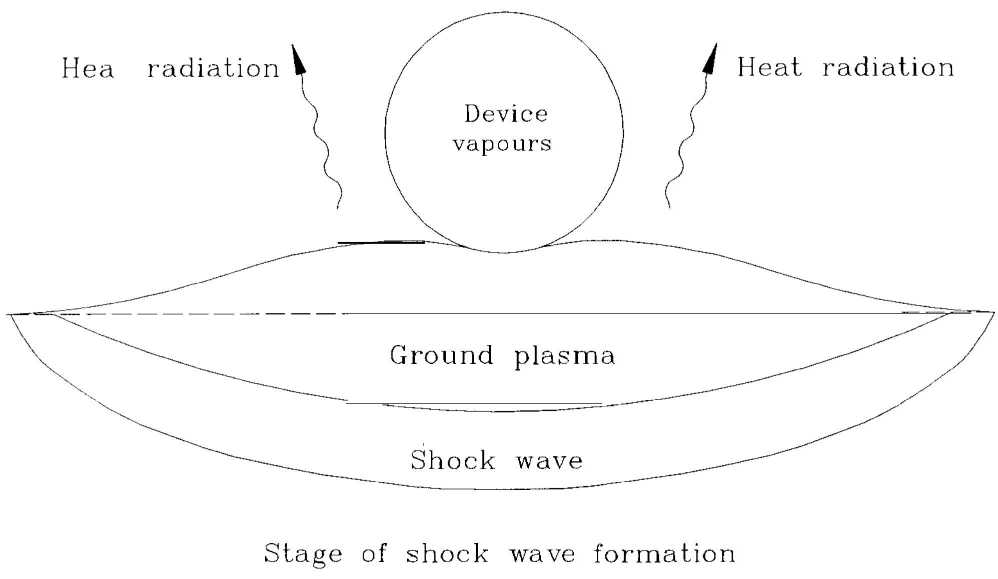
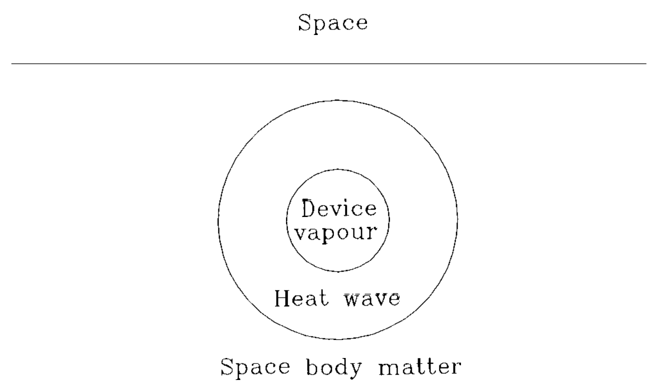


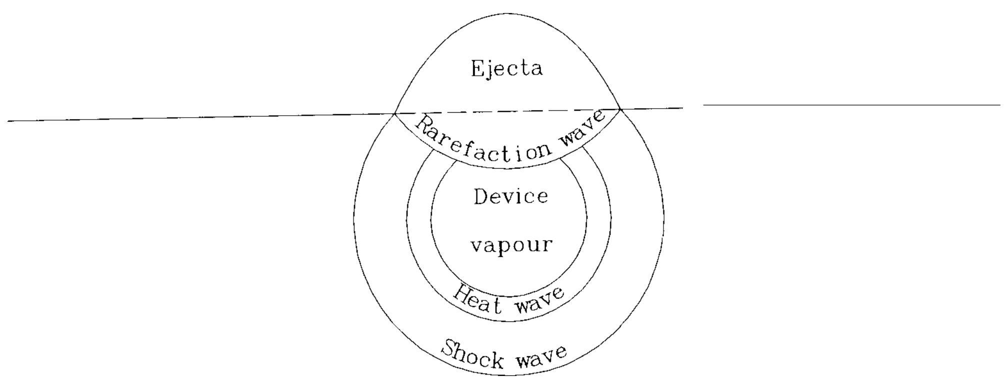
X– ray and heat wave stage



Stage of shock wave formation



Heat wave stage



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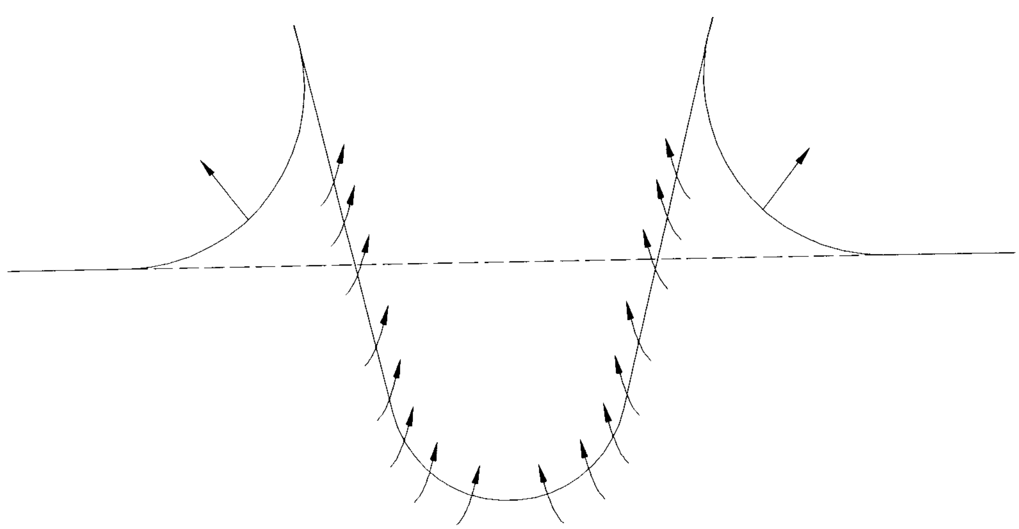

Stage of cratering formation

EFFECT OF THE UNDERGROUND NUCLEAR EXPLOSION